Recall: A *basis* of vector space V is any subset $B \subseteq V$ such that ① B is lin. ind. ② B spans V.

"The only lin comb. giving 0_V is the zero-combination" *

"Every vector in V is a linear comb. of vectors from B" *

Prop: B is a basis of V iff every vector of V arises as a unique lin. comb of elts from B.

Recall: $\dim(V) \stackrel{*}{=}$ number of elements in a basis for V.

Ex: $\mathbb{R}^n$ has dimension n: $\mathcal{E}_n = \{e_1, e_2, \cdots, n\}$.

Recall: $L : V \to W$ is *linear* when for all $u, v \in V$ and all $c \in \mathbb{R}$ we have $L(u + c \cdot v) \stackrel{*}{=} L(u) + c \cdot L(v)$.

NB: easiest condition to check...

The *rank* of L is $\dim(\text{ran}(L))$.
The *nullity* of L is $\dim(\ker(L))$. *

→ *range* of L is $\text{ran}(L) = \{L(v) : v \in V\}$
↳ i.e. set of outputs of function L

→ *kernel* of L is $\ker(L) = \{v \in V : L(v) = 0_W\}$
↳ i.e. set of vectors mapping to 0_V under L.

Rank-Nullity Formula: $\dim(\text{dom}(L)) = \text{rank}(L) + \text{nullity}(L)$.

Ex: $D = \left\{ \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \right\}$. Show D is dependent.

Method: $a\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} + b\begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + c\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$ solve!

$$\begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & -1 \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\left[\begin{array}{ccc|c} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & -1 & 0 \end{array}\right] \rightsquigarrow \left[\begin{array}{ccc|c} 1 & 0 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 1 & -1 & 0 \end{array}\right] \rightsquigarrow \left[\begin{array}{ccc|c} 1 & 0 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{array}\right]$$

No leading 1.

<u>Note</u>: leading 1's are in columns 1, 2.

So $\left\{ \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \right\}$ is a <u>basis</u> of span(D).

Thus D is linearly dependent.

$$\text{Span}(D) = \left\{ a\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} + b\begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + c\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} : a, b, c \in \mathbb{R} \right\}$$

We can rewrite $\text{RREF}\begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & -1 \\ 0 & 0 & 0 \end{bmatrix}$

$\therefore$ in the system: $\begin{cases} a + c = 0 \\ b - c = 0 \end{cases} \rightsquigarrow \begin{cases} a = -c \\ b = c \end{cases}$

Point $-c\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} + c\begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + c\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$

$\therefore$ when $c = 1$: $-\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} = 0_V$

$[\ v_3 = v_2 - v_1$

$$\therefore \text{Span}(D) = \{ a v_1 + b v_2 + c v_3 : a, b, c \in \mathbb{R} \}$$
$$= \{ a v_1 + b v_2 + c(v_2 - v_1) : a, b, c \in \mathbb{R} \}$$

$$= \{ \underbrace{(a-c)}\, v_1 + \underbrace{(b+c)}\, v_2 \;:\; a, b, c \in \mathbb{R} \}$$

$$= \{ \alpha v_1 + \beta v_2 \;:\; \alpha, \beta \in \mathbb{R} \}.$$

$$\mathrm{span}(D) = \mathrm{span}(D \setminus \{v_3\})$$

$$a\begin{pmatrix}1\\1\\0\end{pmatrix} + b\begin{pmatrix}0\\1\\1\end{pmatrix} + c\begin{pmatrix}1\\0\\-1\end{pmatrix} = \begin{pmatrix}x\\y\\z\end{pmatrix}$$

$$\to \begin{array}{ccc} a & b & c \\ \downarrow & \downarrow & \downarrow \end{array} \left[\begin{array}{ccc|c} 1 & 0 & 1 & x \\ 1 & 1 & 0 & y \\ 0 & 1 & -1 & z \end{array}\right] \rightsquigarrow \left[\begin{array}{ccc|c} 1 & 0 & 1 & x \\ 0 & 1 & -1 & -x+y \\ 0 & 1 & -1 & z \end{array}\right]$$

$$\rightsquigarrow \left[\begin{array}{ccc|c} 1 & 0 & 1 & x \\ 0 & 1 & -1 & -x+y \\ 0 & 0 & 0 & \boxed{x-y+z} \end{array}\right]$$

condition on the span :)

$\Rightarrow$ D is not spanning b/c the system is not solvable ... for $x=y=0$, $z=1$ b/c $x-y+z=1\neq 0$.

i.e. $\begin{pmatrix}0\\0\\1\end{pmatrix} \notin \mathrm{span}(D)$.

So $\mathrm{span}(D) = \left\{ \begin{pmatrix}x\\y\\z\end{pmatrix} \in \mathbb{R}^3 : x-y+z=0 \right\}$

Ex: Is $S = \left\{ \begin{pmatrix}1&0\\0&1\end{pmatrix}, \begin{pmatrix}1&1\\0&0\end{pmatrix}, \begin{pmatrix}0&1\\1&0\end{pmatrix}, \begin{pmatrix}0&0\\1&1\end{pmatrix} \right\}$ ~~lin ind.~~ basis ?

Sol: $x\begin{pmatrix}1&0\\0&1\end{pmatrix} + y\begin{pmatrix}1&1\\0&0\end{pmatrix} + z\begin{pmatrix}0&1\\1&0\end{pmatrix} + w\begin{pmatrix}0&0\\1&1\end{pmatrix} = \begin{pmatrix}a&b\\c&d\end{pmatrix}$

iff $\begin{pmatrix} x+y & y+z \\ z+w & x+w \end{pmatrix} = \begin{pmatrix} {}^{a}0 & \overset{b}{0} \\ {}_{c}0 & \underset{d}{0} \end{pmatrix}$ Legend: Pink replaces zeros..

iff $\begin{cases} x+y & = 0 \; a \\ \quad y+z & = 0 \; b \\ \qquad z+w & = 0 \; c \\ x \qquad +w & = 0 \; d \end{cases}$

so solve system: $\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0\,a \\ 0 & 1 & 1 & 0 & 0\,b \\ 0 & 0 & 1 & 1 & 0\,c \\ 1 & 0 & 0 & 1 & 0\,d \end{array}\right]$

show ~~this has only 0-solution, so they're~~ LI. $\boxed{\checkmark}$

Ex: $L : P_3(\mathbb{R}) \to M_{2\times 2}(\mathbb{R})$

$$L(a+bx+cx^2+dx^3) = \begin{bmatrix} a+b & b+c \\ c+d & a+d \end{bmatrix}.$$

Compute $\ker(L)$ and $\operatorname{ran}(L)$ (give bases!).

Sol: First compute $\ker(L)$.

$a+bx+cx^2+dx^3 \in \ker(L)$

$\iff L(a+bx+cx^2+dx^3) = 0_W$

$\iff \begin{bmatrix} a+b & b+c \\ c+d & a+d \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$

$\iff \begin{cases} a+b & = 0 \\ \quad b+c & = 0 \\ \qquad c+d & = 0 \\ a \qquad +d & = 0 \end{cases} \rightsquigarrow$ reduce $\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 \end{array}\right]$

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 \end{array}\right] \rightsquigarrow \left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & -1 & 0 & 1 & 0 \end{array}\right]$$

$$\rightsquigarrow \left[\begin{array}{cccc|c} 1 & 0 & -1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \end{array}\right]$$

$$\rightsquigarrow \left[\begin{array}{cccc|c} 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

$$\therefore \left\{\begin{array}{l} a \qquad\qquad + d = 0 \\ \quad b \qquad\quad - d = 0 \\ \qquad\quad c + d = 0 \\ \qquad\qquad\quad 0 = 0 \end{array}\right. \rightsquigarrow \left\{\begin{array}{l} a = -t \\ b = t \\ c = -t \\ d = t \end{array}\right.$$

$$\text{So } \ker(L) = \{-t + tx - tx^2 + tx^3 : \underline{t \in \mathbb{R}}\}$$

$$= \{t(-1 + x - x^2 + x^3) : t \in \mathbb{R}\}$$

$$= \operatorname{span}\{-1 + x - x^2 + x^3\}.$$

Hence $\{-1 + x - x^2 + x^3\}$ is a basis of $\ker(L)$.

<u>NB</u>: $\#\{-1 + x - x^2 + x^3\} = 1$, $\operatorname{nullity}(L) = \underline{1}$.

To compute a basis for range:

$$\operatorname{ran}(L) \overset{*}{=} \{L(v) : v \in \operatorname{dom}(L)\}$$

$$\underset{*}{=} \{L(a + bx + cx^2 + dx^3) : a, b, c, d \in \mathbb{R}\}$$

$$= \left\{ \begin{bmatrix} a+b & b+c \\ c+d & a+d \end{bmatrix} : a,b,c,d \in \mathbb{R} \right\}$$

$$= \left\{ a\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + b\begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} + c\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + d\begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix} : a,b,c,d \in \mathbb{R} \right\}$$

$$= \operatorname{span}\left\{ \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix} \right\}$$

$$\underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} - \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}} = \begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix}$$

$$= \operatorname{span}\left\{ \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}}_{\text{shw LI.}} \right\}$$

$\therefore \left\{ \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \right\}$ is a basis.

So $\operatorname{rank}(L) = 3$.

Alt-Rank Computation: $\dim(\operatorname{dom}(L)) = 4$

$\operatorname{nullity}(L) = 1$

$\therefore$ by Rank-nullity formula: $4 = 1 + \operatorname{rank}(L)$

$\therefore \operatorname{rank}(L) = 3$. $\boxtimes$